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FLAME SHAPES OF LUMINOUS NONBUOYANT LAMINAR COFLOWING JET DIFFUSION FLAMES

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Introduction. Laminar diffusion flames are of interest as model flame systems that are more tractable for analysis and experiments than practical turbulent diffusion flames. Certainly understanding laminar flames must precede understanding more complex turbulent flames while many laminar diffusion flame properties are directly relevant to turbulent diffusion flames using laminar flamelet concepts [1]. Laminar diffusion flame shapes have been of interest since the classical study of Burke and Schumann [2] because they involve a simple nonintrusive measurement that is convenient for evaluating flame structure predictions. Motivated by these observations, the shapes of laminar flames were considered during the present investigation. The present study was limited to nonbuoyant flames because most practical flames are not buoyant. Effects of buoyancy were minimized by observing flames having large flow velocities at small pressures [3]. Present methods were based on the study of the shapes of nonbuoyant round laminar jet diffusion flames of Lin et al. [4] where it was found that a simple analysis due to Spalding [5,6] yielded good predictions of the flame shapes reported by Urban et al. [7] and Sunderland et al. [8].

Earlier studies of the shapes of nonbuoyant laminar jet diffusion flames generally considered round hydrocarbon-fueled flames burning in still air, see Refs. 4-9 and references cited therein. These studies raise several concerns, however, as follows: what conditions are needed to minimize effects of buoyancy at normal gravity, how important are transient effects when limited times at microgravity are used to produce nonbuoyant flames, and what is the effect of soot luminosity on flame shape measurements? With respect to minimizing effects of buoyancy at normal gravity, use of low pressures [3] and large flow velocities [9] are proven tactics that will be exploited here. Transient flame development effects have been problematical using ground-based low-gravity facilities due to the limited test times of drop towers and the flight path disturbances of aircraft facilities. Recent measurements from long-term low gravity tests in space [7] and drop tower tests at reduced pressures [8], however, have minimized transient flame development problems and yielded results that could be correlated by simplified theories as mentioned earlier. Effects of soot luminosity on the shapes of hydrocarbon-fueled laminar jet diffusion flames in air are also a problem. The luminosity of hydrocarbon-fueled flames generally is caused by glowing soot particles; therefore, relationships between luminous flame dimensions and the location of the flame sheet (where the local mixture fraction is stoichiometric) is an issue because the latter generally is associated with predictions of flame shapes. Past measurements of laminar soot-containing laminar diffusion flames indicate that luminous/stoichiometric flame lengths are in the range 0.9-1.8 with the largest values observed as the laminar smoke point is approached [10-12]. This behavior occurs because soot oxidation begins at slightly fuel-rich conditions and can continue in the fuel-lean region for a time before the soot is either consumed or soot oxidation is quenched and the soot cools below temperatures where it glows yellow [4,8]. Fortunately, flame shapes at these limiting conditions could still be correlated using the simplified Spalding [5] analysis after defining an empirical parameter to represent effects of soot luminosity [4]. Such empiricism is not desirable but it appears to be unavoidable pending better understanding of soot reaction processes. The shapes of laminar coflowing jet diffusion flames (at the limit where fuel and air (oxidant) velocities were the same) have received little attention since the classical study of Burke and Schumann [2]. Exceptions include Williams [13] and Malingham et al. [14] who extended Ref. 2 to treat flames where the outer coflowing stream was unbounded. During the present study, the approach of Malingham et al. [14] was further developed to provide a way to correlate the shapes of coflowing jet diffusion flames.

Based on these observations, the objectives of the present investigation were to consider the properties of nonbuoyant round luminous laminar jet diffusion flames in coflowing air, as follows: measure flame shapes for various fuel types and flow conditions, compare these results with earlier findings for flames in still air, and use the measurements to develop a correlation for the shapes of coflowing jet diffusion flames.

Experimental Methods. A coaxial tube burner was used with a 6 mm diameter fuel port and a 60 mm diameter air port. Effects of buoyancy were reduced by observing flames at low pressures within a

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windowed chamber (300 mm dia. x 1200 mm long) with the burner directed vertically upward along the chamber axis. Flame shapes were found from dark field photographs. Test conditions involved acetylene, propylene and 1 - 3 butadiene as fuels in coflowing air with air/fuel velocity ratios of 0.2-32, jet exit Reynolds numbers of 18-121 and ambient pressures of 19-50 kPa.

Theoretical Methods. The objective of analysis was to develop a convenient way to correlate flame shape measurements; thus, a set of easily used equations was sought along with recommendations for selecting properties appearing in these equation as opposed to more complete methods that would require computer solution. The major assumptions are similar to Lin et al. [4], as follows: (1) steady round laminar jet diffusion flame in an unbounded coflowing gas; (2) effects of buoyancy and potential energy changes small; (3) small Mach numbers so that viscous dissipation and kinetic energy changes can be ignored; (4) flame has a large aspect ratio so that streamwise diffusion can be ignored; (5) for the same reasons, the solution of the governing equations can be approximated by far-field (integral invariant) conditions; (6) all chemical reactions occur in a thin flame sheet; (7) mass (all species), momentum and energy diffusivities are the same; (8) constant thermophysical and transport properties; and (9) effects of radiation are small. Solution of the governing equations is illustrated by Malingham et al. [14] and Schlichting [15]. The flame length, L_f , relative to a virtual origin, L_o , normalized by the fuel port diameter, d , becomes:

$$(L_f - L_o)/d = C_f \text{ Re Sc} / (16 Z_u) \quad (1)$$

where C_f is an empirical coefficient to correct for soot luminosity, Re is the burner Reynolds number, Sc is the Schmidt number and Z_u is the stoichiometric mixture fraction. The corresponding expression for the luminous flame diameter, w , becomes

$$w/d = (-g (u_{f,o} / u_{a,o}) \ln\{g\} / Z_u)^{1/2} \quad (2)$$

where

$$g = (x - L_o) / (L_f - L_o) \quad (3)$$

and $u_{f,o}$ and $u_{a,o}$ are the initial fuel and air stream velocities. Notably, the present results agree with Burke and Schumann [2] and Malingham et al. [14] for the limiting condition where initial fuel and air velocities are the same and as the diameter of the outer stream becomes large.

Results and Discussion. Measured and predicted flame lengths in coflowing and still air are plotted in Fig. 1. All the measurements are plotted as suggested by the simplified theories of flames in coflowing and still air. Properties are obtained from Braun et al. [16]. Values of Sc and the mean molecular viscosity used to compute Re were based on the properties of air at the mean flame temperature from Braun et al. [16]. The results in Fig. 1 for flames in still gases from the space based LSP experiments yield an excellent correlation with $C_f = 1.13$; these lengths are roughly twice as long as the measurements of Sunderland et al. [8] for soot free flames which is quite reasonable based on the soot-luminosity/stoichiometric-flame-length ratios mentioned earlier. The present measurements of luminous flames for $u_{a,o} / u_{f,o} > 1$ also yield a good correlation in terms of Eq. (1) with $C_f = 1.05$. this implies L_f (still air) / L_f (coflow) $\approx 3/2$, independent of $u_{a,o} / u_{f,o}$ and Re in accord with the simplified theories. Finally, present results for small coflow velocities, $u_{a,o} / u_{f,o} < 0.5$, also crudely agree with the no coflow correlation but yield slightly shorter flames due to enhanced mixing from coflow.

Flame diameters at the flame halflength, $w_{1/2}$, are plotted as suggested by the theory, Eq. (2), in Fig. 2. The agreement between measurements and predictions is seen to progressively improve as the normalized flame length increases and the flames better approximate the far-field assumptions of the theory. These results imply that $w_{1/2}$ progressively decreases as the coflow velocity increases.

Finally, some typical measured and predicted flame shapes are illustrated in Fig. 3 for acetylene flames having progressively increasing $u_{a,o} / u_{f,o}$ and progressively decreasing jet exit Reynolds numbers. It is evident that the simplified theory does an excellent job of estimating the variations of flame length and flame shape in the region not too close to the burner exit. The latter deficiency is expected, however, as a limitation of the far-field assumptions of the analysis. In view of the simplifications of the theories, and the potential complexities of soot luminosity in diffusion flames, the simplified models of flame shapes in still and coflowing air exhibit remarkably good performance.

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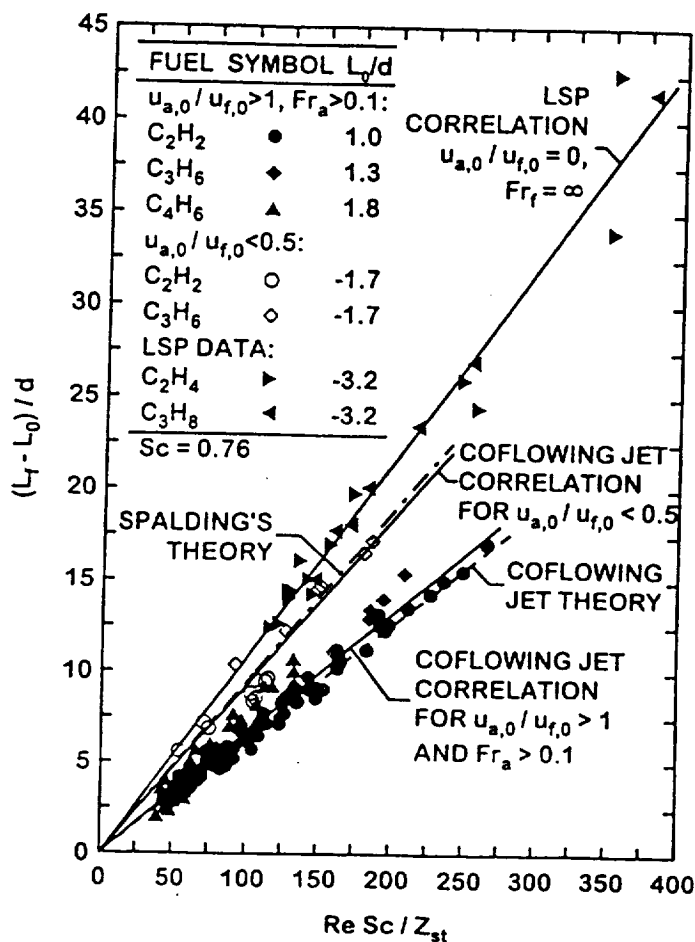


Fig. 1 Luminous flame lengths of jet diffusion flames in still and coflowing air.

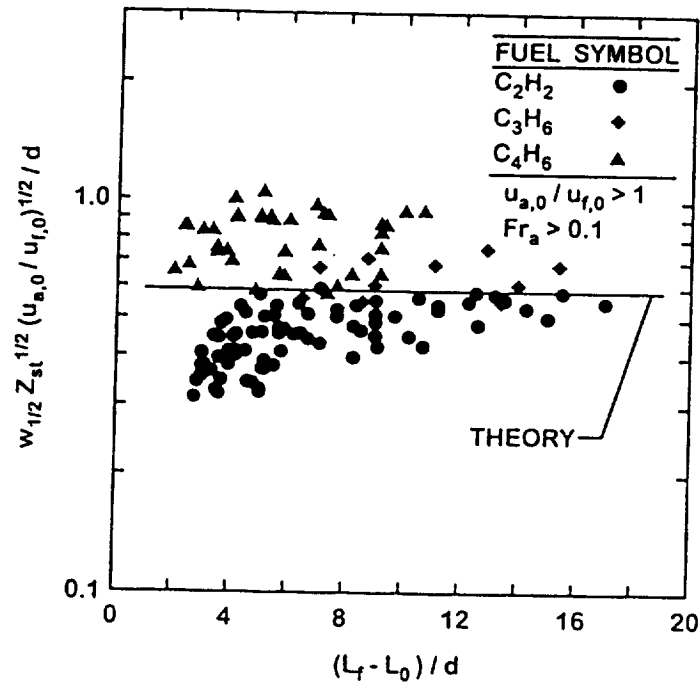


Fig. 2 Luminous flame diameters of coflowing jet diffusion flames.

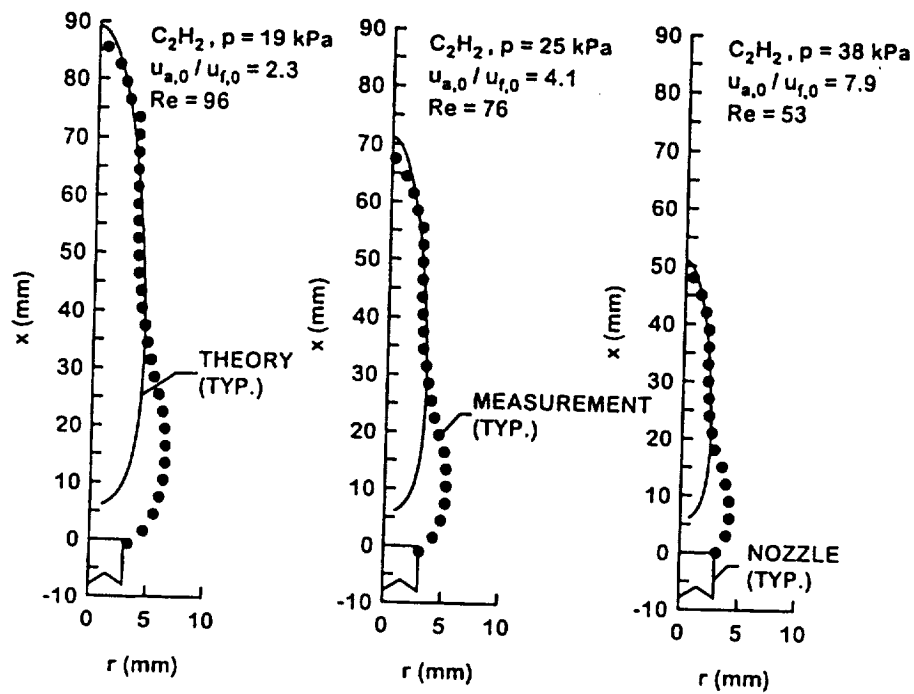


Fig. 3 Luminous flame shapes of coflowing jet diffusion flames.